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Mini Review

Factors Affecting Cement Suspensions Strength for Soil Formations Improvement – A Review

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Abstract

Grouting is a common technical method with many applications, e.g., it is used for soil stabilization and strengthening, for reduction for water ingress to underground facilities or of the water loss through a dam foundation, etc. Grouts comprise several constituents, which are combined in many ways depending on the in-situ conditions and the outcome desired. The use of very fine cement grouts for injections into fine-to-medium sands has been proposed to circumvent problems associated with the permanence and toxicity of chemical grouts and the inability of ordinary cement grouts to permeate soil formations finer than coarse sand. The strength of a suspension is the property of probably most interest in cases where the main objective of a soak injection program is to improve the mechanical properties of the soil. The object of this paper is to investigate the effect of cement physical properties, water-to-cement ratio, additives and chemical improvers on the strength of cement suspensions.

Introduction

The construction of underground structures on soft ground often requires the soil to be improved in order to ensure the safety and the stability of surrounding buildings. The improvement of the properties and mechanical behavior of the soil formations is of particular interest because it has a direct impact on bearing capacity problems [1,2], stability of slopes and embankments [3-5] as well as permanent seismic movements of slopes [6]. Permeation grouting is commonly used in geotechnical engineering either to reduce the permeability or improve the mechanical properties of soil and rock [7]. The strength of a suspension is the property of probably most interest in cases where the main objective of a soak injection program is to improve the mechanical properties of the soil. Mainly, the durability of a suspension is divided into short-term and long-term. Short-term is defined as the strength that a suspension exhibits up to a few hours after its preparation and can be determined using a pocket penetrometer. Long-term strength is determined by performing unimpeded compression tests and corresponds to the strength that a suspension develops over days, months or even years. In general, the age of 28 days is considered as a common reference point among researchers for the long-term durability of a suspension. To improve cement grout strength, research efforts in recent years have focused on the use of special cements composed of very fine particles, like fine and ultrafine cements [8-14].

Effect of Cement Properties on Suspensions Strength

The rate of strength development of a slurry depends significantly on the fineness [15] and chemical composition of the cement. It is known that the strength at 28 days of a suspension based on common Portland cement type I (according to ASTM) is approximately equal to 60-70% of the final strength of the suspension, while this percentage is reached after 3 days in the case of using common type III (ASTM) Portland cement [16]. The granulometric gradation and especially the fineness of the cement has a significant effect on the strength of the suspensions. In general, fine cement slurries have been found to yield higher strengths than slurries based on common Portland cement [15,17]. Nevertheless, it seems that at relatively low water-to-cement ratios (≤1:1) this effect is reversed. Specifically, Santagata & Collepardi [18] showed that the strength of cement slurries with a maximum grain size of 20μm is higher than the strengths of slurries with cements having a maximum grain size of 17μm and 9μm (30 MPa vs. 27.5 MPa and 25 MPa, respectively for W/C=0.72). Other results show that the suspension of common cement (W/C = 1:1) gave a strength equal to 53.89 MPa, while the equivalent of fine-grained cement 25.13 MPa [15], while in suspensions with W/C ratios 0.6:1 and 1:1 the strengths were equal to 29.0 MPa and 23.2 MPa for common Portland cement and 26.1 MPa and 16.7 MPa for fine cement, respectively [19]. It is also observed that slurries based on cements containing slag are stronger than pure Portland cement slurries. In particular, it appears that the best combination is achieved for cements consisting of 75% slag and 25% Portland cement [20].

Effect of Curing Time on Suspensions Strength

Regardless of the strength development rate of a suspension, increasing the curing time causes an increase in strength [21]. Characteristically, results are reported, showed that the 24-hour-old suspension strength, which ranged from 7.5 MPa to 17.5 MPa, reached a range from 13.3 MPa to 23.8 MPa at 7 days and from 26.0 MPa to 30.0 MPa after 28 days [22]. This increase may continue for several years after the suspensions are made and this is a parameter that depends entirely on the type of cement and the conditions prevailing in the field. For example, it has been shown that the strength of a suspension undergoes reductions - which can be significant - with decreasing temperature. Furthermore, a method (AMEBA) has been proposed for predicting the strength of cement materials at older ages knowing the strength at two initial ages [23]. The equations used based on this method are as follows:

$$f_{ca} = \frac{f_{cm}^{AMEBA}}{f_{cb}^{AMEBA-1}}$$

$$AMEBA = \frac{\left[\left(\frac{1}{t_a^n}\right) - \left(\frac{1}{t_b^n}\right)\right]}{\left[\left(\frac{1}{t_m^n}\right) - \left(\frac{1}{t_b^n}\right)\right]}$$

where f_{ca} is the old age strength required to be calculated, while f_{cm} and f_{cb} are the middle and young age strengths respectively.

AMEBA is a function, which depends on the three ages and a moderating factor that depends on the characteristics of the materials and the prevailing conditions. Where t_a, t_b, t_m are the long, short and medium ages of the specimens, respectively, and n is the moderating factor, which has been observed to take a value equal to 0.5 for Portland cement with and without pozzolan admixtures and limestone. When the cement contains significant percentages of blast furnace slag then the factor appears to depend on the fineness and quantity of the cement.

Effect of Water-To-Cement Ratio (W/C) on Suspensions Strength

The effect of the water-to-cement ratio is considered the most important, it has been widely investigated and it has been verified that an increase in its value causes a dramatic decrease in the strength of the suspension [21,24]. As typical unimpeded compressive strength values of pure suspensions with water-to-cement ratios equal to 0.5:1, 1:1, 2:1 and 3:1, Reinhardt [25] reports 60 MPa, 10 MPa, 3 MPa and 2 MPa, respectively. Additionally, Littlejohn [16] states that the unimpeded compressive strength of a suspension can be determined based on the equation:

$$UCS = \frac{A}{B^{1.5\cdot(W/C)}}$$

where UCS is the unimpeded compressive strength, A is a strength constant equal to 96,526 MPa and B is a dimensionless constant that depends on cement characteristics and age. For example, the constant B for a slurry based on type I (ASTM) cement, aged 28 days, takes a value equal to 5. It is emphasized that for the best application of the equation, the oozing exhibited by the slurry should be almost zero and complete hydration of the cement is achieved. For this reason, its use should be limited to suspensions with an W/C ratio between 0.3:1 and 0.7:1.

Effect of Additives Presence on Suspensions Strength

The effect of additives presence on the strength of cement suspensions has been extensively investigated and firm conclusions have already been reached for some of them. For example, it is now accepted that the addition of bentonite causes a reduction in the strength of cement slurries [26] due to reduced exudation and the increase in porosity it causes and for this reason the content of bentonite should be limited to low percentages (2%-5%) [16]. The use of bentonite allows the preparation of suspensions with a wide range of strength values [27] that can even approach 15.0 MPa [28,29] proposed the following equation, with which it is possible to determine the unconfined compressive strength of bentonite-cement slurries as a function of the W/C ratio:

$$UCS=K/((W/C)^n)$$

where K is a coefficient that depends on the ratio of bentonite to cement and takes values ranging from 5000 to 20000 and the index n takes values from 1.4 to 2.9.

On the other hand, the addition of silica fume can lead to an increase in the strength of the pure suspension [30], while similar results are possible to achieve with the addition of fly ash [27]. The use of fly ash/cement suspensions is considered an effective solution in cases where cavity filling is required where the strength requirement rarely exceeds 5.0 MPa [27]. In this case, the amount of ash should be carefully controlled, as the use of sufficiently low water-to-solids ratios leads to the preparation of very dense and unpumpable suspensions due to the high-water absorbency exhibited by ash [31], while the use of sufficiently high fly ash to cement ratios leads to a dramatic reduction in slurry strength [27]. The addition of sand to cement suspensions causes a decrease in strength, but this is not considered significant in cases where the ratio of sand to water is of the order of 10% [29], while the addition of natural pozzolan also causes a decrease in strength [22]. In general, with the use of the above additives it is possible to prepare cement suspensions with strengths ranging from 0.40 MPa to 30.0 MPa [27].

Effect of Chemical Improvers on Suspensions Strength

The use of chemical improvers does not have a specific effect on the strength of cement suspensions. Their positive or negative effect depends on the way in which they participate in the hydration process, the content with which they participate in a suspension and the compatibility they show with the rest of the components of the suspension and especially with cement. Specifically, it is reported that the use of retarders [29] causes an increase in the strength of cement suspensions, while the use of superplasticizers [26] and viscosity improvers [32] can lead to small or large reductions in strength. Also, a decrease in strength due to an increase in the content of the superfluidizer is reported by Ballivy et al. [33] and Sarkar & Wheeler [34], while Saric-Coric et al. [32] report that the use of polymelamine superplasticizers is more beneficial for suspension strength than the use of polynaphthalene sulfonate superplasticizers.

Conclusion

Based on the results obtained and the observations made during this investigation, the following conclusions may be advanced:

a. The rate of strength development of a slurry depends significantly on the fineness and chemical composition of the cement. It is known that the strength at 28 days of a suspension based on common Portland cement type I (according to ASTM) is approximately equal to 60-70% of the final strength of the suspension, while this percentage is reached after 3 days in the case of using common type III (ASTM) Portland cement.

b. The granulometric gradation and especially the fineness of the cement has a significant effect on the strength of the suspensions. In general, fine cement slurries have been found to yield higher strengths than slurries based on common Portland cement. Nevertheless, it seems that at relatively low water-to-cement ratios (≤ 1:1) this effect is reversed.

c. Regardless of the strength development rate of a suspension, increasing the curing time causes an increase in strength. A method (AMEBA) has been proposed for predicting the strength of cement materials at older ages knowing the strength at two initial ages.

d. The effect of the water-to-cement ratio is considered the most important, it has been widely investigated and it has been verified that an increase in its value causes a dramatic decrease in the strength of the suspension.

e. The addition of bentonite causes a reduction in the strength of cement slurries due to reduced exudation and the increase in porosity it causes and for this reason the content of bentonite should be limited to low percentages (2-5%).

f. The addition of silica fume can lead to an increase in the strength of the pure suspension, while similar results are possible to achieve with the addition of fly ash.

g. The addition of sand to cement suspensions causes a decrease in strength, but this is not considered significant in cases where the ratio of sand to water is of the order of 10%, while the addition of natural pozzolan also causes a decrease in strength.

h. The use of chemical improvers does not have a specific effect on the strength of cement suspensions. Their positive or negative effect depends on the way in which they participate in the hydration process, the content with which they participate in a suspension and the compatibility they show with the rest of the components of the suspension and especially with cement.

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